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Mulder, Machiel; Zeng, Yuyu

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Exploring interaction effects of climate policies: A model analysis of the power market☆

Machiel Mulder*, Yuyu Zeng

Department of Economics, Econometrics and Finance, Faculty of Economics and Business, University of Groningen, The Netherlands

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ABSTRACT

The effectiveness of climate policy strongly depends on how these measures are implemented. National policy measures may have international spillover effects which partly neutralize domestic emission reduction, while different types of policy measures may offset each other as well. This paper explores the conditions for these interaction effects by using a concise partial-equilibrium two-country model of the electricity market which also includes a system for emissions trading. We find that the international spillover effects not only depend on the integration of electricity markets, but also on the tightness of the emissions-trading system. We show that this tightness is negatively related to the degree the supply of renewable energy is stimulated. We find that the more renewable energy is stimulated, the less domestic reduction in carbon emissions is offset by spillover effects. A more binding cap in the emissions-trading system makes national policies less effective. Hence, if climate-policy measures such as subsidies for renewable energy make the cap in the trading scheme less binding, these climate-policy measures become more effective.

1. Introduction

In order to reduce carbon emissions in the power sector, governments are implementing a set of policy measures. These measures vary from subsidies for renewable-energy techniques to taxes on fossil-fuel electricity production and mechanisms for trading in emission rights. While some measures are taken on national level, others have an international character. Within the EU, the implementation of climate policies is pursued by the European Commission. The Renewable Energy Directive (2009/28/EC), for instance, sets a binding target of 20 percent final energy consumption from renewable sources by 2020. Each EU Member State has to realize the renewable-energy target, but these countries are free to choose their own policies to stimulate deployment of renewable-energy sources. EU countries utilize different measures for this purpose, such as feed-in-tariff subsidies and quota systems (Haas et al., 2010). In addition to this, several countries are considering to impose constraints on conventional power plants, in particular coal-fired power plants (EIA, 2014; EZ, 2015). These measures vary from implementing additional environmental standards (e.g. on fuel efficiency or emissions per unit) making

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* Corresponding author at: Faculty of Economics and Business, Nettelbosje 2, 9747 AE Groningen, The Netherlands.
E-mail address: machiel.mulder@rug.nl (M. Mulder).

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it complicated if not impossible for (old) coal-fired power plants to operate or imposing a carbon tax which in particular raise the generation costs of coal-fired power plants. Besides this set of different national policy measures to reduce carbon emissions by the power sector, an emissions-trading system has been implemented on EU level. This EU Emission Trading System (ETS) is the largest cap and trade mechanism for CO_2 emissions in the world. It sets up a cap on the total amount of CO_2 emitted by installations of firms subject to this scheme. This cap is annually reduced in order to realize an overall reduction in carbon emissions. The initial allocation of the cap to participants was initially done by grandfathering, but more and more auctioning is used as allocation method (European Commission, 2012). In the secondary market, participants can trade in permits which results in a carbon price. Meanwhile, the European Commission is promoting the integration of national electricity markets to facilitate border-free trading across Europe, see (Keay, 2013). As a result, national power markets have become more closely integrated with each other, which may increase the international spillovers of national climate policies.

It is well established in economic literature that the coexistence of different types of climate policies may have counteracting effects (Schmalensee, 2012; Goulder, 2013; Böhringer et al., 2016). This holds in particular when a cap-and-trade emissions scheme is implemented. In that case, theoretically, the level of emissions is only determined by the cap in the emissions-trading scheme (Tietenberg, 2006). If the cap remains the same, other instruments only affect the costs of reaching that target, but not the amount of emissions. If an emissions trading scheme is combined with subsidies for solar panels, for instance, it can be expected that the emissions within the power sector are reduced which lowers the overall demand for and, hence, the price of emissions permits, which in turn can stimulate other firms participating within the emissions trading scheme to raise their emissions since emitting has become cheaper (see e.g. van den Bergh et al., 2013; Böhringer and Rosendahl, 2011). This effect is called the waterbed effect of climate policy.

In this paper, we explore the conditions for the interaction effects to occur. For that purpose, we analyze the interaction of three types of policy measures to realize a transition of the electricity industry based on fossil fuels towards an industry with a lower level of carbon emissions. These policy measures are subsidies for renewable electricity, a carbon tax for fossil-fuel power plants and an international emissions trading scheme. The choice for these three types of policy measures (emissions trading, subsidies renewables and carbon tax) is based on the fact that all three types of measures are currently implemented or discussed, albeit to a different extent in several European countries. In the Netherlands, for instance, the government recently decided to implement a carbon tax on top of the European emission trading scheme and several domestic support schemes for renewable energy in order to realize a minimum price for carbon. In this paper we do not discuss the pros and cons of the individual climate-policy instruments as subsidies, taxes and emissions trading. Although one can discuss which instrument is best equipped to realise carbon reduction in a cost-effective way (see e.g. Aldy et al., 2010), in practice governments use packages of different types of instruments (Hughes and Urpelainen, 2015; Kautto et al., 2012; Del Rio and Mir-Artigues, 2014; Sijm, 2005). Therefore it is also important to understand how they influence each other.

As we want to analyze the interaction among various climate-policy measures, we build a concise stylized model of two connected electricity markets combined with a regional emissions-trading market. In this model, some electricity producers are perceived as strategic players, hence they can exercise market power and influence the wholesale prices. Such a model is fairly well equipped to simulate the situation with a few centralized power producers, as it exists in several European countries such as the Dutch and German electricity market (see also Willems et al., 2009; Mulder et al., 2015; ten Cate and Lijesen, 2004). We take the stochastic nature of both supply and demand into account. Firms base their decisions regarding investments and the dispatch of plants on expected values for weather conditions, load levels and scarcity levels. Including probability distributions for wind and demand allows us to control for the volatility of market conditions in the power market. International trade is based on price-arbitrage opportunities. The size of the cross-border transmission capacity determines the potential magnitude of international trade and, hence, the potential cross-border spillover effects. The two countries in this model differ in size, so we have a large and a small country. Differences in scale of countries are important to consider in order to better assess international spillover effects from policies implemented in the different countries. One may expect that the magnitude of the spillover effects are highest when they originate from a large country and affect a neighboring country smaller in size. As an international carbon permit market is added to the electricity market, the carbon price is part of the variable generation costs of fossil-fuel producers. In addition, countries may implement a carbon tax on electricity producers. In order to also analyze the international spillover effects of different national policies, we assume that the carbon tax is only implemented in one country at the same time. Countries are also able to stimulate renewable-electricity generation by giving subsidies which are financed by a tax on electricity consumption. The model is calibrated to more or less reflect the current characteristics of the German and Dutch power market. The objective of this calibration is just to have a reasonable benchmark for the numerical analysis, not to make realistic simulations of the power markets in these countries. The numerical analysis remains of a stylized nature with the purpose to explore the conditions for the occurrence of interaction effects among climate-policy instruments.

Using the numerical application of our model, we find that combining the three different climate-policy measures, including an emissions-trading system, may have a net effect on the level of carbon emissions, despite of the above-mentioned waterbed effect. This result comes from the fact that the carbon price in the trading scheme has a floor, i.e. it can never be lower than zero. This means that when other climate-policy measures are effective in reducing the demand for permits, they may also neutralize the waterbed effect. Our findings show that implementing national policies on top of an international emissions trading scheme can still be effective in reducing carbon emissions. As a matter of fact, although adding a carbon tax on top of an emissions trading scheme may result in more emissions reductions as the waterbed effect does not always work, this does not mean that such a policy is efficient.

The remainder of this paper is organized as follows. We review relevant literature in Section 2. In Section 3, we describe the key elements of the partial equilibrium model of the wholesale electricity market and define how the market equilibrium is determined. Section 4 presents the results for the policy variants. Section 5, finally, concludes.

2. Literature

This paper builds on and contributes to the literature of power market modeling and interaction effects of climate policies. A key question regarding the modelling of the electricity market is how to deal with strategic behaviour. Willems et al. (2009) compare two oligopolistic models of the electricity market: Cournot and Supply Function Equilibrium.[1] They show that both models explain roughly the same fraction of the observed price variations in the German electricity market. Furthermore, they suggest to use Cournot model for short-term model analysis as such a model can easily accommodate additional market conditions such as network constraints. Mulder et al. (2015) apply the Cournot model to the Dutch electricity market taking both the intermittent wind energy supply and fringe suppliers by Combined Heat and Power (i.e., CHP) into account. As a result of the intermittent and fringe supplies, the wholesale prices tend to be lower. Using a competitive equilibrium model without strategic behavior among power generators, Saguan and Meeus (2014) investigate the interaction between cross-border transmission investments and renewable-energy policies. Their main conclusion is that renewable energy trade in order to comply with each member state targets is beneficial for both zones, but that an imperfect regulatory framework for transmission investment creates a significant cost for realising renewable-energy targets. In our model, some "big" producers are perceived as strategic players, hence they can exercise market power and influence the wholesale prices. Such a model fairly well resembles the situation with a few centralized power producers, such as in the Dutch and German electricity market.

Using several different models including partial equilibrium models and general equilibrium models, Calderón et al. (2016) find significant CO_2 reductions through high carbon prices and abatement targets in Colombia. Benavente (2016) uses a computable general equilibrium model to examine the impact of a carbon tax in Chile. They conclude that such a policy is effective at reducing carbon emissions but at the cost of GDP losses. Ellerton and Fullteron (2014) find that a carbon tax on electricity in the U.S. can generate net negative domestic leakage as it raises the costs for other industries, which results in lower demand and, hence, lower production levels and carbon emissions by these industries. This impact of higher costs in the power industry on overall carbon emissions was also found by McKibbin et al. (2014). These authors conclude that the domestic carbon emissions outside the power sector decrease as higher electricity prices slow overall economic activity. Note that the above-mentioned papers only consider domestic carbon tax to reduce domestic carbon emissions. In a more than one country setting, Elliott et al. (2010) confirms that a uniform tax among all member countries is effective at reducing carbon emissions.

In the above mentioned literature, the analysis of interaction of carbon taxes with other climate policies is not taken into account. From literature on emissions trading we know that the coexistence of different types of climate policies may have counteracting effects. When a cap-and-trade emissions scheme is implemented, the level of emissions is determined by the cap in the emissions-trading scheme (Tietenberg, 2006). If the cap remains the same, other instruments only affect the costs of reaching that target, but not necessarily the amount of emissions (see e.g. van den Bergh et al., 2013). As a result, the final level of emissions remains unchanged while the contribution of different emitters to this overall level has changed, which raises the costs of reaching the cap. Böhringer and Rosendahl (2011) find that the costs of realising a CO_2 reduction target of 25% increase by more than 60% if the percentage renewable energy is stimulated by more than 10%. In other words: in case of an emissions-trading scheme, other measures directed at realising emission reduction merely affect the level as well as the allocation of costs of reaching the emission cap among the participants of the trading scheme without affecting the overall level of emissions (i.e. the benefits in terms of reductions of emissions remain the same). Because of this interaction effect, Böhringer (2014) concludes in his overview of two decades of European Climate policy, that renewable-energy subsidies and energy-efficiency mandates can result in higher costs for realising energy savings, energy efficiency improvements, and fuel switching than in case of a stand-alone cap-and-trade system. The effectiveness of climate policy can also seriously be reduced through carbon leakage. Caron et al. (2015), for instance, show that the cap-and-trade emissions trading scheme in California may result in an increase of emissions in neighboring markets which may neutralize about half of the realized reduction by the scheme.

From these papers, we learn that combining different types of climate-policy measures reduces the cost-effectiveness of climate policy. This strand of literature also states that adding other policy instruments to a system of emissions trading does not result in any additional emissions reduction (Sijm, 2005; Sorrell and Sijm, 2003). The arguments in favour of other policy measures, such as subsidies for renewable energy, are derived from the perceived benefits in terms of learning effects or security of energy supply. The contribution of our paper is that we analyse the conditions under which the interaction occurs or does not occur. In particular, we analyse in which circumstances climate-policy measures such as subsidies for renewables

[1] Cournot equilibrium assumes that producers compete in the production quantity while the Supply Function Equilibrium assume that producers compete by bidding complete supply functions instead of one single quantity in an oligopolistic market with demand uncertainty.

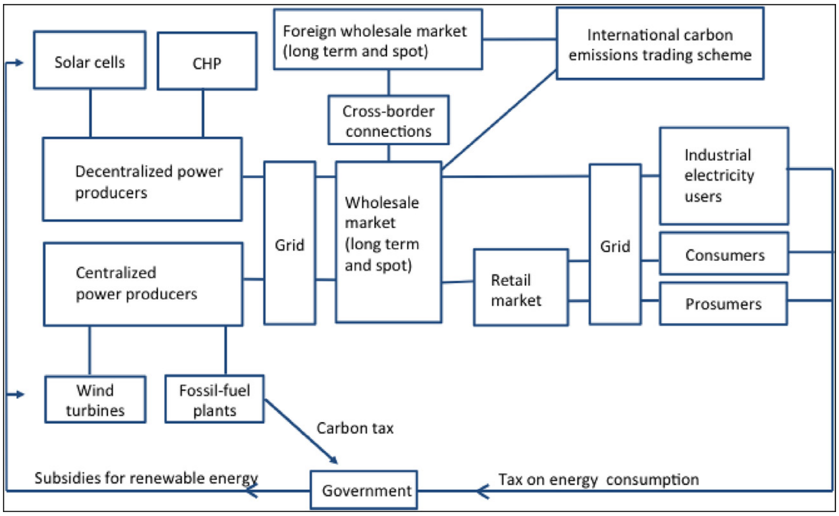

Fig. 1. Framework of a two-country model of the electricity market with climate-policy instruments.

and taxes on fossil-fuel use have an additional reducing effect on carbon emissions when also an emissions-trading scheme exists.

3. Concise model of the electricity market

In order to analyse the interaction of different types of climate-policy measures, we develop and apply a concise stylized two-country model of the electricity market plus a regional emissions-trading scheme. The framework of this model is depicted in Fig. 1. In the following sections, we introduce the corresponding components in detail.

3.1. Supply side

On the supply side, the electricity market is composed of both centralized and decentralized power producers. The set of centralized power producers in country c is denoted as $N_c = \{1, 2, \ldots, n_c\}$. In general, n_c is taken to be a small number. For example, in the Dutch electricity market, there are only a few major electricity producers (ENGIE, E. ON Benelux, Essent (part of RWE) and Nuon (now subsidiary of Vattenfall)). In most cases, the power market is operated on a hourly basis. Therefore, we model the electricity market hourly and $h \in \{1, 2, \ldots, 24\}$ denotes hours in a day throughout the whole year. The years are indexed by $y \in \{1, \ldots, \bar{y}\}$. The model is simulated such that "1" represents the current situation and "$\bar{y}$" denotes the end year. Note that p_{cyh} is the wholesale price per hour in country c year y.

The energy mix employed by producers consists of fossil-fuel fired plants (F) including gas and coal-fired plants, wind turbines (W), solar cells (S) and combined heat and power (H). The energy resources for centralized power producers include fossil-fuel plants and wind turbines. Note that the difference between fossil-fuel plants and wind turbines is that the costs on the margin for the wind turbines are almost zero, while the marginal costs for fossil-fuel plants are not zero and also include CO_2 prices. We do not consider technology upgrades to reduce the marginal costs of fossil-fuel plants as we may assume that these are constant in the short term.

Assumption 1. Each centralized power producer $i \in N_c$ has the same constant marginal cost $m_c \in \mathbb{R}_+$ for fossil-fuel plants over year y in country c.

Note that we do allow different fossil-fuel production techniques in these two countries. Hence, the constant marginal costs might differ between them. The deployment of wind energy mainly depends on the weather conditions and is stochastic, *ex ante*. Let w_h denote the capacity factor at hour h to exploit the wind energy capacity. Because of the geographical proximity of neighboring countries, we assume that the production by wind turbines is subject to the same stochastic pattern in both countries.

Assumption 2. We assume that w_h follows a certain discrete distribution, with realizations $\mu_h^j \in \mathbb{R}_+$ and each realization μ_h^j has a probability $\pi_h^j \in \mathbb{R}_+$. Note that $\sum_j \pi_h^j = 1$.

Note that q_{cyh}^i is composed of the production amount by fossil-fuel plants and also wind turbines, hence

$$q_{cyh}^i = q_{cyh}^{iF} + q_{cyh}^{iW}, \tag{1}$$

Note that q^{iF}_{cyh} and q^{iW}_{cyh} are the production part by fossil-fuel plants and wind turbines, respectively. And the realized wind energy production is calculated based on the realized capacity factor and the installed generation capacity,

$$q^{iW}_{cyh} = \mu^{j}_{h} \times Q^{iW}_{cy}. \tag{2}$$

At the beginning of a certain year, each centralized power producer's wind energy capacity Q^{iW}_{cy} is given and is assumed to be common knowledge. Note that the production amount is constrained by the generation capacity Q^{iF}_{cy} and Q^{iW}_{cy}, hence we have $q^{iF}_{cyh} \leq Q^{iF}_{cy}$ and $q^{iW}_{cyh} \leq Q^{iW}_{cy}$. The aggregate fossil fuel generation capacity in country c year y is denoted as Q^{F}_{cy} and $Q^{F}_{cy} = \sum_{i \in N_c} Q^{iF}_{cy}$. The firms can invest in fossil-fuel generation capacity each year and we denote ΔQ^{F}_{cy} as the investment in fossil-fuel plants in country c year y.

Because of the large number of decentralized power producers, they are modeled as price-takers which cannot exercise market power to influence wholesale market prices. Hence, the decentralized power producer equalizes their marginal benefits to their marginal costs. The aggregate decentralized power production (D) only uses combined heat and power (DH), and solar cells (DS). Costs on the margin from wind and solar energies production are assumed to be zero while combined heat and power is a side product of the horticultural suppliers, whose main objective is to produce heat for their greenhouses. We assume that they have increasing marginal costs (see also Mulder et al., 2015).

Assumption 3. The production amount by combined heat and power q^{DH}_{cyh} is assumed to be a linear function of electricity prices,

$$q^{DH}_{cyh} = \alpha_D + \beta_D p_{cyh},$$

where $\alpha_D > 0$ and $\beta_D > 0$.

In addition, the expected production amount by solar cells is the product of the hourly capacity factor and the installed generation capacities. Let u_h be the expected capacity factor of solar cells at hour h. Hence, we have the following,

$$q^{DS}_{cyh} = u_h \times Q^{DS}_{cy},$$

where Q^{DS}_{cy} denotes the yearly generation capacity for solar cells. The sum of CHP and solar cells composes the aggregated production amount by fringe suppliers,

$$q^{D}_{cyh} = \alpha_{cyh} + \beta p_{cyh}, \tag{3}$$

where $\alpha_{cyh} = \alpha_D + u_h \times Q^{DS}_{cy}$ and $\beta = \beta_D$.

3.2. Demand side

The demand side of the wholesale electricity market consists of large electricity users (L) and retailers (R). Retailers sell electricity further to consumers and prosumers. We assume a linear demand function for large electricity users as follows:

$$p_{cyh} + t^L + \tau_h = a^L_h - b^L_h q^L_{cyh}, \tag{4}$$

where a^L_h and b^L_h are parameters to be calculated, t^L is the tax rate for large electricity users and τ_h is the hourly network tariff paid by large electricity users. Hence, we implicitly assume that the tax rate and network tariffs do not change over time y.

The retail price is equal to the wholesale market price (p_{cyh}), plus a retail margin (r), taxes (or levies) t^R and the dynamic network tariffs τ_h. Hence, the demand function for consumers and prosumers can be specified as following,

$$p_{cyh} + t^R + r + \tau_h = a^R_h - b^R_h q^R_{cyh}, \tag{5}$$

where a^R_h and b^R_h are parameters to be calculated. The aggregation of the demand from large users and retailers induces the total demand function faced by producers,

$$q_{cyh} = q^L_{cyh} + q^R_{cyh} = a_h - b_h p_{cyh}, \tag{6}$$

where a_h and b_h are calculated from Eqs. (4) and (5) and,

$$a_h = \frac{a^L_h - t^L - \tau_h}{b^L_h} + \frac{a^R_h - t^R - r - \tau_h}{b^R_h},$$

$$b_h = \frac{1}{b^L_h} + \frac{1}{b^R_h}.$$

Note that by introducing a dynamic network tariff τ_h, we move the aggregate demand function upward or downward on a hourly basis, but the slope of the aggregate demand function does not change. Therefore, the aggregate demand function suppresses demand when there is a higher network tariff τ_h and boosts demand when the network tariff is low.

3.3. Market equilibrium

The wholesale electricity market is modeled as an imperfect market. Facing a certain demand curve, the producers compete in terms of quantities. The market reaches equilibrium when each producer's strategy is the best response to the strategies actually employed by its competitors. Domestic electricity demand is met by centralized producers and the aggregate decentralized production, hence

$$q_{cyh} = \sum_i q^i_{cyh} + q^D_{cyh}. \tag{7}$$

And the residual demand faced by i is given by,

$$q^i_{cyh} = a_h - b_h p_{cyh} - q^{-i}_{cyh} - \alpha_{cyh} - \beta p_{cyh}, \tag{8}$$

where q^{-i}_{cyh} denotes the sum of the other centralized producers' production amount except i. Note that in the above equation, we have replaced q^D_{cyh} by Eq. (3). Rearranging Eq. (8), we obtain,

$$p_{cyh} = \frac{a_h - \alpha_{cyh} - q^i_{cyh} - q^{-i}_{cyh}}{b_h + \beta}, \tag{9}$$

In practice, forward contracts play an important role in electricity wholesale markets. Electricity producers sell a part of their generation in forward markets. Allaz and Vila (1993) have shown that firms have an incentive to do so as this may reduce the market power of competitors in the spot market. As a result of the sale of electricity in forward markets, the competition in the spot markets is more fierce which has a price reducing effect, while the actual production is higher (see also Mulder et al., 2015). Because of this relationship between forward and spot market competition, we explicitly control for the impact of forward markets sales on the actual production level of the strategic players. Hence, we assume that centralized power producers are active in the forward market. Let q^{if}_{cyh} be the forward trading quantity by firm i and p^f_{cyh} be the forward price. Following Allaz and Vila (1993), "under perfect foresight, equilibrium requires the forward market to be efficient. This means that the forward price as a function of the forward positions must be equal to the price that will result from the Cournot competition on the spot market given these positions. Therefore, no arbitrage is possible." Given the forward positions by each firm, firms compete over the production quantity in the spot market. Hence, the production quantity has to be solved as a function of the forward positions. Then firms optimize their forward positions given the quantity solved from the production period, see Allaz and Vila (1993). Note that in our model part of the production is met by wind energy.

All the derivations for the optimal production and forward positions are included in Appendix C. We have the following results for the market equilibrium,

Proposition 4. *Under the following conditions,*

1. *The decentralized power production is given by Eq. (3);*
2. *The aggregate demand function is given by Eq. (6);*
3. *The demand is satisfied by centralized power producers and decentralized power production;*
4. *The ex post production from wind energy is calculated based on actual capacity factor μ^j_h and generation capacity (Eq. (2));*
5. *Centralized power producers use both fossil fuels and wind energy (Eq. (1));*

We have the following result: the optimal production amount using fossil fuels by firm i at hour h and time y is given by,

$$q^{iF}_{cyh} = \frac{n_c\left(a_h - \alpha_{cyh} - m_c(b_h+\beta)\right) - q^{iW}_{cyh} - n_c(q^{iW}_{cyh} + q^{-iW}_{cyh})}{n_c^2 + 1};. \tag{10}$$

From Eq. (10), we can easily see that any production by wind turbines will replace the electricity generation by fossil-fuel plants for producer i. For each value of the capacity factor for wind turbines π^j_h, we would have a corresponding market equilibrium regarding fossil-fuels production (10) and wholesale prices (9).[2]

3.4. International trade and law of one price

In this section, we further investigate how import and export influence the domestic price, which is determined by (9). If there are price differences between the two countries, we assume that traders will profit from export from a lower price

[2] In the model calibration and policy analysis, we also put an additional constraint that the hourly changes within the fossil-fuel electricity production are within a certain range in order to control for dynamic dispatch constraints.

country to a higher price country.[3] For country c, let IE_{cyh} be the net export amount in hour h year y, i.e., export minus import. Let p^u_{cyh} be the uniform prices between these two countries together with trading amount IE_{cyh}, hence we have the following

$$p^u_{cyh} = \frac{a_h - \alpha_{cyh} - \sum_i q^i_{cyh} + IE_{cyh}}{b_h + \beta}. \tag{11}$$

Note that q^i_{cyh} are solved from Eq. (10) together with the *ex ante* expected wind energy production.[4] In addition, we have

$$p^u_{S,yh} = p^u_{L,yh}, \tag{12}$$

and

$$IE_{S,yh} + IE_{L,yh} = 0. \tag{13}$$

Combining Eqs. (11)–(13), we solve for the corresponding p^u_{cyh} and IE_{cyh}. In the second step, we check for the capacity constraint IU between these two countries. If $IE_{S,yh} > IU$, then the (absolute) size of the import and export is equal to the capacity constraint while the different prices p^d_{cyh} in both country are as follows:

$$p^d_{S,yh} = \frac{a_h - \alpha_{S,yh} - \sum_i q^i_{S,yh} + IU}{b_h + \beta},$$
$$p^d_{L,yh} = \frac{a_h - \alpha_{L,yh} - \sum_i q^i_{L,yh} - IU}{b_h + \beta}.$$

If $IE_{S,yh} < -IU$, then the cross-border flows are in the opposite direction while the prices in both countries are as follows:

$$p^d_{S,yh} = \frac{a_h - \alpha_{S,yh} - \sum_i q^i_{S,yh} - IU}{b_h + \beta},$$
$$p^d_{L,yh} = \frac{a_h - \alpha_{L,yh} - \sum_i q^i_{L,yh} + IU}{b_h + \beta}.$$

3.5. Carbon market and the interaction with the electricity market

Finally, we add an international carbon permit market to the set of national electricity markets. The electricity industry is assumed to be the only participant in this market. Let cap_y be the carbon emission cap and PCO_{2y} be the average CO_2 price. For each fossil-fuel production technique, the carbon emission coefficient is denoted as e_c. In such a setting, the adjusted constant marginal costs ac_{cy} for country c in year y are as follows:

$$ac_{cy} = m_c + \mathrm{PCO}_{2y} \times e_c. \tag{14}$$

Given the constant marginal costs ac_{cy}, we calculate the fossil-fuel production according to Eq. (10). Then we compare the actual aggregated carbon emissions over a period with the emission cap for that period. If the carbon emissions are above the cap, we keep increasing the carbon prices until the emissions are equal to or below the cap. Hence, the carbon price is determined by the cap and the aggregated demand for carbon permits.

3.6. Banking of permits

In the EU ETS, allowances can not only be freely used within a phase (the current phase being 2013–2020), but also saved until the next phase. This saving of permits is called banking. In the above analysis we did not control for this banking option. In order to analyse the impact of banking on the model results, we also run a sensitivity analysis where firms can freely transfer any permit which is not used to the next period.

This is modelled as follows: if the aggregated level of emissions during a period is below the cap for that period, then we assume that all unused permits (which is equal to the difference between cap and emissions) is transferred to the next period, raising the actual cap in that period.

[3] We do not make any assumption on the type of connection between markets and how traders can make use of cross-border capacity, but we do take into account the existence of a cross-border constraint. Note that in the first step of the calculation, we allow traders to equalize the prices between these two countries not hindered by a cross-border transmission constraint. In the second step, we control for this constraint.

[4] For notational convenience, we denote the two countries as “L” and “S”.

Table 1
Parameters chosen for the small and large countries.

	Small country	Large country
Number of centralized producers	5	8
Constant variable generation costs (Euro/MWh)	35	30
Wind power generation capacity (GW)	2.9	57.5
Solar power generation capacity (GW)	1.1	22.5

4. Numerical analysis

4.1. Parameters, scenarios and policy variants

In order to analyse the interaction effects between climate-policy measures, we conduct a numerical analysis with our model. We refer to a two interconnected region case where we have a large and small country. Differences in scale of countries are important in order to better assess international spillover effects from policies implemented in the larger country to the smaller country. The parameters for both countries are derived from the characteristics of Germany (large) and Netherlands (small), respectively, just to have a benchmark for the calibration but without the objective of fully representing these countries or making a specific policy analysis for these countries. Table 1 lists a brief summary of relevant parameters we have used in this paper.

According to the Statline database of Statistics Netherlands, the installed capacity for wind energy including onshore and offshore wind parks is roughly 2.9 GW in 2014.[5] Most wind energy production in the Netherlands is run by centralized power producers. The capacity factor per hour to employ the wind power generation capacity is calculated based on the data from the Dutch Royal Meteorological Institute.[6] The installed capacities for wind power generation in Germany are taken to be about 57.5 GW. Because of the geographical proximity, the capacity factor of wind energy production in Germany is assumed to have the same discrete distribution per hour as in the Netherlands.

Decentralized power production mainly refers to CHP and solar energy. The minimum run capacity for CHP in the Netherlands and Germany is estimated to be 5 GWh. We roughly estimate that $\alpha_D = 5000$ and $\beta_D = 30$. The installed solar generation capacity in 2014 are around 1.1 GW in the Netherlands and 22.5 GW in Germany.[7] We could calculate the solar cells hourly capacity factor u_h based on the historical data from 2006 to 2014.

Details of how we calculate the hourly aggregate demand function are reported in Appendix D. The electricity consumption amount and wholesale prices are based on a load profile. Price elasticities are based on the results in the literature for the electricity market, see Lijesen (2007). We have taken hourly price elasticities and in general, a higher elasticity for off-peak hours and a lower elasticity for peak hours (9–20 h). All hourly elasticities are in the range of −0.3 and −0.2.

In order to keep the model simulations as simple as possible, we approach each year by simulating only 24 consecutive hours.[8] Hence, we ignore weekly and seasonal fluctuations in demand and supply and treat the outcome of a 24-simulation as representative for all hours in a year. For the simulation of the emission trading scheme, for instance, this means that the model works with a daily cap and daily price, but this cap and this price must be seen as the annual cap and the average annual price.

As the supply and demand conditions may vary strongly over year to year, we work with scenarios regarding wind speed and demand levels.[9] For each wind speed level, we use a probability, based on empirical evidence for the Netherlands. In order to define the hourly probability distribution we use actual hourly data on wind speed. We rank the hourly data from lowest to highest level and then determine the average value in three classes: the lowest 31%, the next 38% and the highest 31% of all observations. Table 3 gives the results for the wind speed. For the demand level, we scale up or down the intercept a_h of the inverse demand function. For each scaling factor, we assign a corresponding probability and this holds for each hour. Table 2 reports the result for demand level in each hour.

Note that for each hour, we have 3 possible realizations of the wind energy capacity factor and 3 scalings of the demand. Therefore, we end up with 9 scenarios for each hour. Running the model for each hour for each scenario, we obtain for each hour a probability distribution of all results. This Monto-Carlo type of analysis enables us to deal with the impact of extreme circumstances, in particular regarding the impact of renewables on the electricity market and the emissions-trading scheme.

5 http://statline.cbs.nl/Statweb/selection/?DM=SLEN&PA=83109ENG&LA=EN&VW=T accessed on November 5, 2015.
6 http://www.knmi.nl/home.
7 Data source: https://en.wikipedia.org/wiki/Solar_power_in_the_Netherlands.
8 Otherwise we would need to simulate 8760 h per year, which would cost a lot of computation time for a model with imperfect competition with stochastic distributions of external factors, while adding such complexity is not needed for the purpose of our analysis.
9 The intermittent character of renewables as well as the stochasticity of demand is dealt with by scenarios where we have distributions for both. The model is run for a number of scenarios. In each scenario a specific (joint) distribution of wind and demand occurs. Implicitly we assume that the firms have full certainty about which scenario they are in. In other words, we implicitly assume that there is no deviation between the expectations for the short run and the realisation. Hence, one can also say that we ignore the problems of balancing and programme responsibility. We believe we can ignore these issues, as that would complicate the analysis tremendously, while it is not needed for the objective or our analysis.

Table 2
Inverse demand intercept scaling factors.

a_h Scaling factor	Probability
0.8	0.31
1	0.38
1.2	0.31

Table 3
Wind power capacity factor with probabilities in each hour.

Hour	Low capacity with prob 0.31	Medium capacity with prob 0.38	High capacity with prob 0.31
1	0.005	0.056	0.397
2	0.005	0.056	0.397
3	0.005	0.056	0.397
4	0.005	0.056	0.423
5	0.005	0.056	0.397
6	0.007	0.063	0.423
7	0.008	0.071	0.451
8	0.011	0.089	0.479
9	0.013	0.110	0.541
10	0.016	0.121	0.573
11	0.023	0.146	0.607
12	0.027	0.160	0.642
13	0.032	0.171	0.678
14	0.032	0.174	0.678
15	0.032	0.160	0.642
16	0.027	0.146	0.607
17	0.020	0.121	0.541
18	0.016	0.099	0.479
19	0.011	0.080	0.451
20	0.008	0.071	0.418
21	0.007	0.063	0.423
22	0.007	0.063	0.423
23	0.005	0.056	0.397
24	0.005	0.056	0.397

Table 4
Matrix representation of 8 policy variants.

		Emission cap level		
		BaseCap	LowCap	HighCap
CarbonTax	No	Baseline	Baseline_LowCap	Baseline_HighCap
	Large country	CarbonTax_L	CarbonTax_L_LowCap	CarbonTax_L_HighCap
	Small country	CarbonTax_S		
CarbonTax or Subsidy RES	No	Baseline_noRES		

Using the above data for the determination of the starting values of the model as well as the probability distributions for the exogenous circumstances, we simulate the electricity market for a period of 15 periods, covering the period 2016 - 2030. Now, we consider 8 policy variants as described in Table 4.

In the "Baseline" variant it is assumed that both countries annually increase the renewable-energy capacity while also a international cap-and-trade emissions trade system exists. The annual increase in RES capacity is based on the assumption that 10% of electricity tax revenues is used to finance the subsidies for these investments. The initial carbon emission cap level is chosen to be 1.04 Mtons per day, which is about equal to the aggregated daily emissions by the power industry in Germany and the Netherlands. In the "Baseline", we assume that the cap is reduced by 0.5% annually. In the policy variants "LowCap" and "HighCap" the cap is annually reduced by 1% and 0.25% respectively. We are in particular interested in the effects of introducing a carbon tax in relation to the tightness of the emissions trading scheme which is represented by the initial level of the cap. In the variants with a carbon tax it is assumed that the larger country imposes a carbon tax of 11.25 euro/MWh on fossil-fuel generation plants.[10] In order to compare the results of the carbon tax, we compare three pairs of variants: Baseline vs CarbonTax_L, Baseline_LowCap vs CarbonTax_L_LowCap, Baseline_HighCap vs CarbonTax_L_HighCap. This allows us to examine the effects of a fossil-fuel tax given different levels of the cap on carbon emission and given a more or less exogenous autonomous growth in renewable-energy capacity. We also compare the variants Baseline, CarbonTax_L

[10] According to the CO_2 emissions coefficients tons per MWh, we have taken 0.3 for gas-fired plants and 0.6 for coal-fired plants in the simulation. For a portofolio of 50% coal-fired and 50% gas-fired fossil-fuel plants with a carbon price of 25 euro per ton, we choose a level of 11.25 euro per MWh for the carbon taxes on top of the fossil-fuel production.

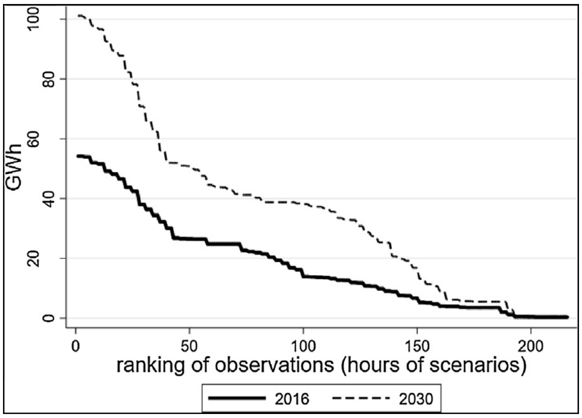

Fig. 2. Duration curves of hourly RES production, Baseline, 2016 and 2030.

and CarbonTax_S to assess the impact of a producer tax in the small country compared to a producer tax in the larger country. Finally, in order to analyse the interaction between the emissions trading scheme and subsidies for renewable energy, we also compare the results of the variants Baseline vs Baseline_noRES. In the former policy variants, emissions trading is combined with subsidies for renewable energy, while in the latter the only climate policy implemented is the emission trading scheme.

4.2. Results

We first present the numerical results for the "Baseline", which is the scenario where both countries stimulate RES by giving subsidies for investments, while also an international cap-and-trade system exists. We are interested in the following metrics: the wholesale electricity prices, the hourly RES production, the utilisation of fossil-fuel plants (defined as average hourly production in percentage of installed capacity), the CO_2 prices and, finally, the CO_2 emissions. Then, we compare this Baseline with the Baseline_noRES where no subsidies for RES are included. Next, we consider the variant of "Prodtax" which imposes a fossil-fuel tax in the large country on top of the "Baseline". Finally, we conduct a sensitivity analysis by changing the emission cap level.[11]

4.2.1. Baseline

As a result of an exogenous stimulation of investments in renewable energy capacity in the "Baseline" variant, this capacity increases strongly. As a consequence, the volatility in the supply by renewables increases strongly as well (Fig. 2). This is related to the fact that the hourly production level by renewables is sometimes close to zero in case of unfavourable weather circumstances independent of the size of installed capacity. Hence, the lowest level of production by renewable energy capacity is hardly affected by the size of this capacity, while the maximum level is strongly related to this (Fig. 2). On average, the hourly renewable energy production is much higher in 2030 compared with the level in 2016. This strong increase in RES capacity fairly well resembles the actual developments in many European countries. The utilisation of fossil-fuel plants in both countries goes down as a result of the increase in RES, see Fig. 13. In addition, the annual reduction in the carbon emission cap raises the scarcity of carbon permits and, hence, the carbon price, see Figs. 4 and 5 . Due to the different size of the initial installed generation capacities, the marginal production is more often run by the RES in the large country and less often in the small country. In the latter country, the upward price effect of the increasing carbon prices dominates the price-reducing effect of the increasing share of RES. As a result, the strong increase of RES significantly reduces the price of electricity (as in the large country), but this appears not to be the case in the small country (see Fig. 3). As the cross-border capacity has a limited size, traders are not able to fully benefit from these price differences. The remaining price differences indicate that this capacity is fully utilized.

4.2.2. Subsidies renewable energy

Before analyzing the interaction between carbon taxes, emissions trading and subsidies for renewables, we first analyze the interaction between the latter two climate policy instruments. The carbon price is significantly higher in the latter variant, as is shown by Fig. 8. This higher price is needed as without subsidies for renewable energy the carbon price needs to do the work to keep the emissions below the cap. Because of the volatility in the carbon prices due to the fluctuations in external circumstances (wind and demand), the carbon price may become (close to) zero now and then as is shown by

[11] Note for Figs. 3–6 : the thickest lines denote the variants with the default cap ("Baseline" and "Prodtax"), the thinnest lines denote the variants with the higher cap ("Baseline_HighCap" and "Prodtax_HighCap") and the lines with intermediate thickness denote the variants with the lower cap ("Baseline_Lowecap" and "Prodtax_LowCap").

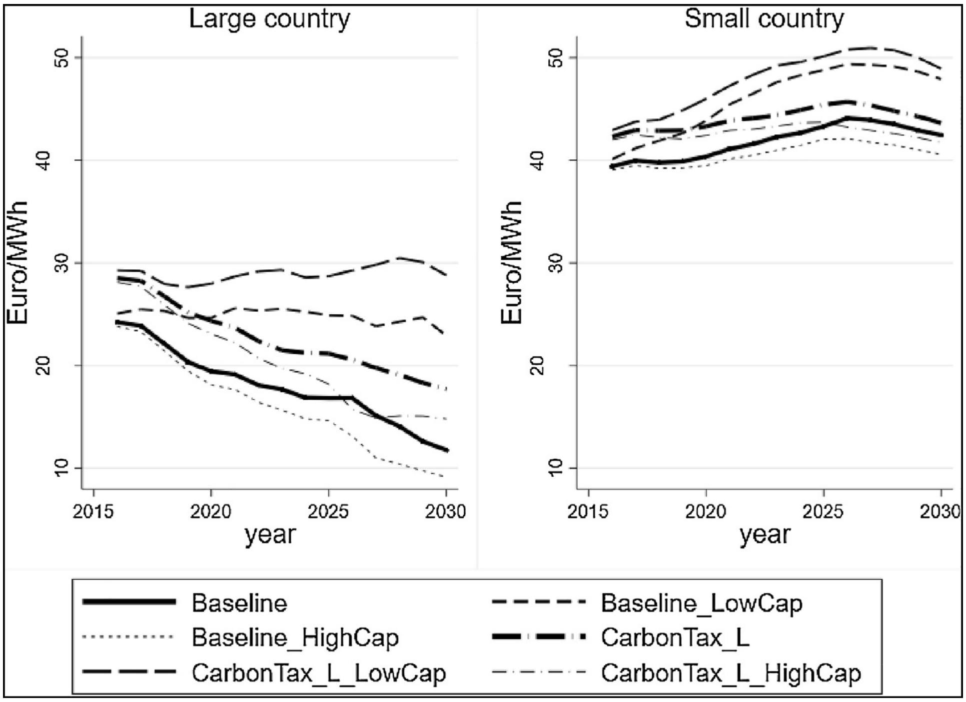

Fig. 3. Average daily wholesale price, large and small country, per variant, 2016–2030.

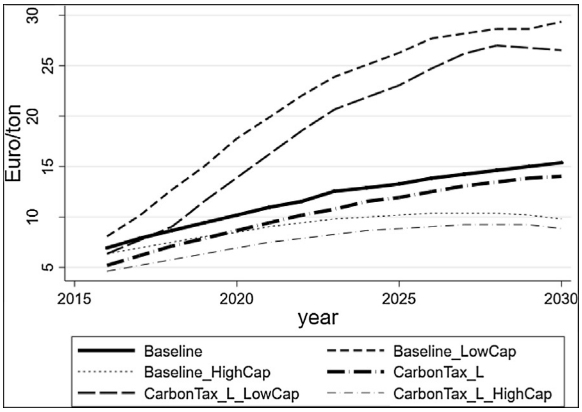

Fig. 4. Average CO_2 price, per variant 2016–2030.

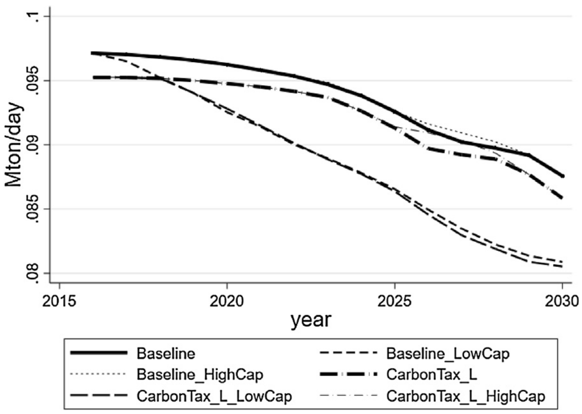

Fig. 5. Aggregated daily CO_2 emissions, per variant, 2016–2030.

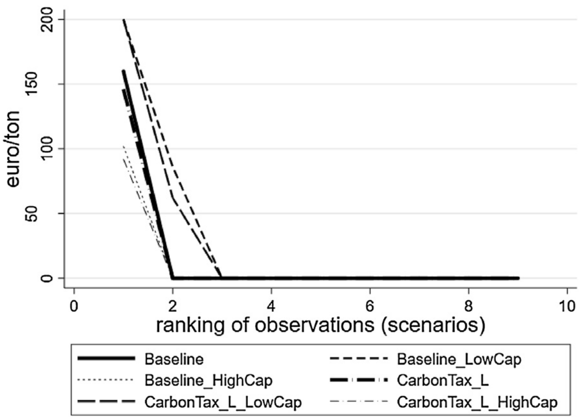

Fig. 6. Duration curve of average daily CO_2 price, per variant, 2030.

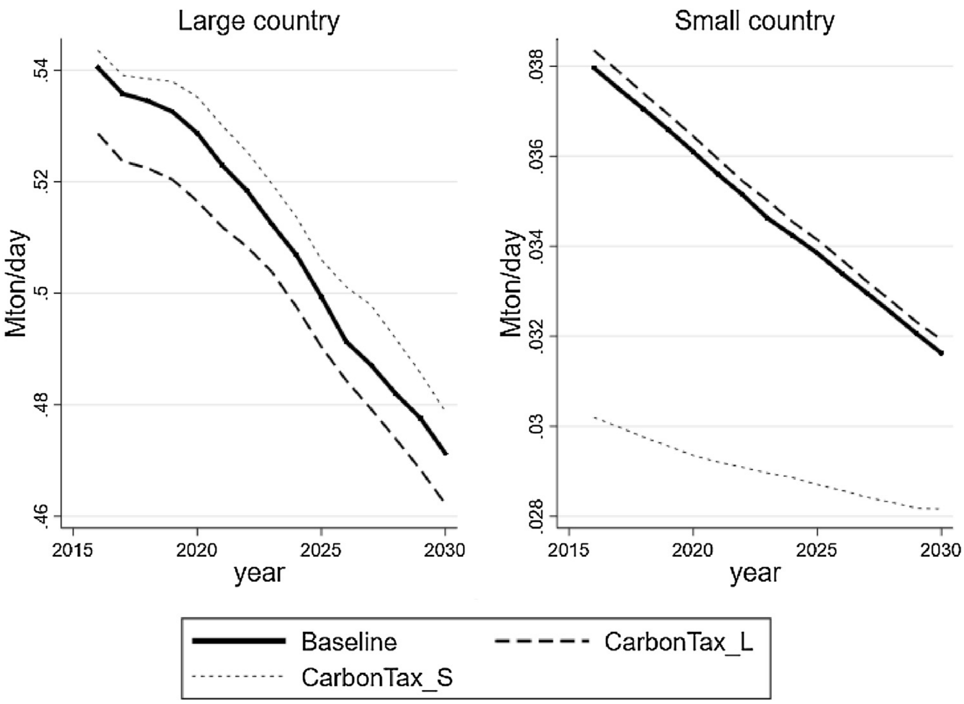

Fig. 7. CO_2 emissions, large and small country, per variant, 2016–2030.

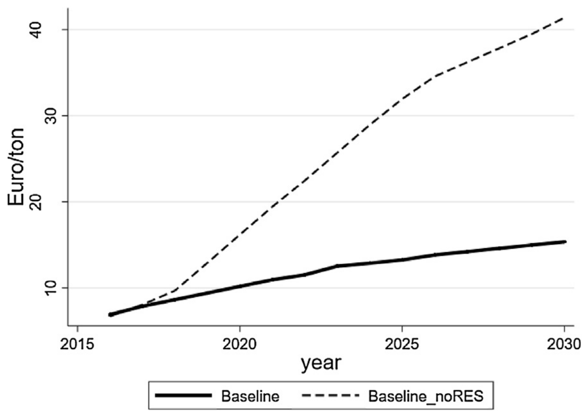

Fig. 8. CO_2 price in Baseline and Baseline_noRES, 2016–2030.

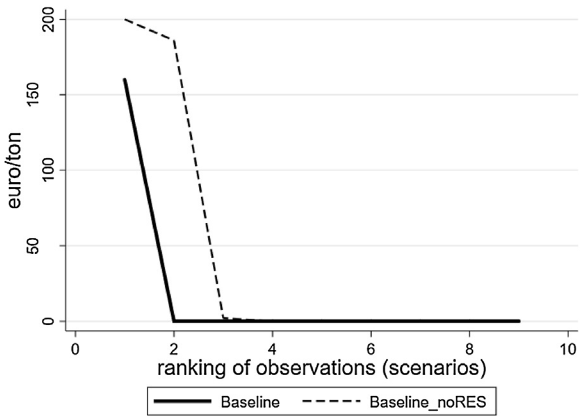

Fig. 9. Duration curve CO_2 price in Baseline and Baseline_noRES, 2016–2030.

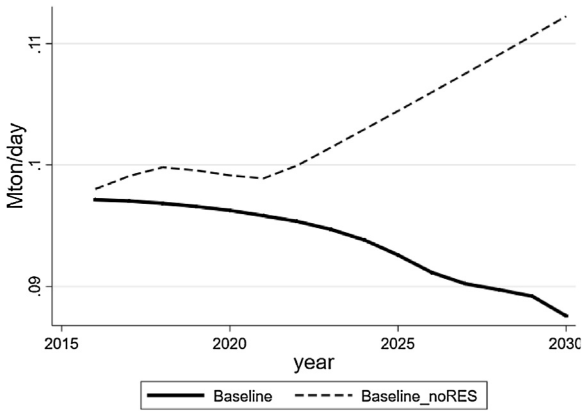

Fig. 10. CO_2 emissions in Baseline and Baseline_noRES, 2016–2030.

Fig. 9. Fig. 10 shows the emissions in the Baseline variant, with both emissions trading and renewable energy investments, and the emissions in the Baseline_noRES variant where emissions trading is the only policy instrument. It appears that in the latter variant the emission levels are higher, which indicates that the subsidies for investments in renewable do have an additional effect on emissions, which is caused by the fact that the waterbed effect does not occur when the carbon price is zero.

4.2.3. Carbon tax

Now, the question is what happens if the large country introduces a carbon tax on top of the measures stimulating the RES capacity and the international emissions trading system. The direct effect is that the generation costs of the fossil-fuel power plants in this country increase. As both countries are connected, the increase in generation costs in the large country implies that this country wants to import from the smaller country in those hours when RES capacity is not setting the price. As a result, production shifts to the smaller country. The introduction of a carbon tax in the large country raises the utilisation of fossil-fuel capacity in the small country (see Fig. 13). Hence, the introduction of a carbon tax in one country results in a carbon leakage. This effect is relatively large when the tax is implemented in the large country (Fig. 7) This international spillover effect of national climate policies also raises the electricity price in the other country, as we observe a price increase in both countries compared with the “Baseline” (Fig. 3).

If the carbon tax is introduced in the small country instead of the large country, the similar type of effects occur albeit smaller. The impact on the CO_2 prices in the region is much smaller, while also the impact on the overall emissions of CO_2 is smaller (Fig. 11). When the small country introduces the carbon tax, the share of renewables in the domestic production increases relatively strongly, while the share in the large country is hardly affected (Fig. 12).

The shift in the location of the production by fossil-fuel plants does, however, not mean that there is no effect on the price of carbon (Fig. 4). The introduction of a carbon tax in one country results in a lower (average) CO_2 price which implies that the overall demand for permits has been reduced. The negative impact of the carbon tax on the carbon price shows the existence of the waterbed effect: the emissions trading system becomes less effective if a carbon tax is introduced. However, we also see that the overall level of carbon emissions is lower when we have a carbon tax, which indicates that the waterbed

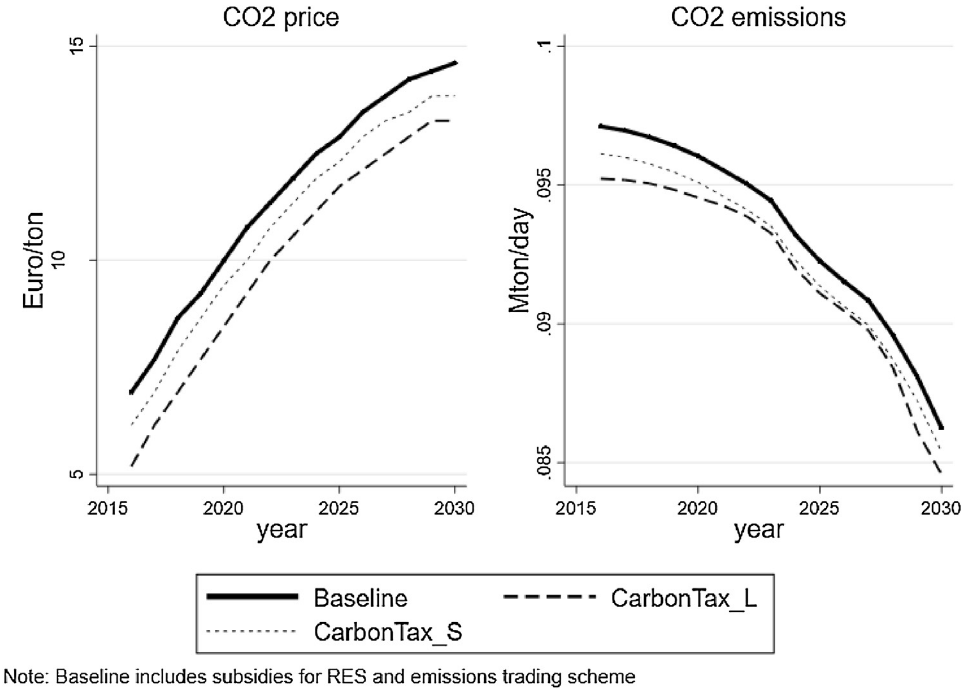

Fig. 11. CO_2 price and emissions, in Baseline and variants with carbon tax, 2016–2030.

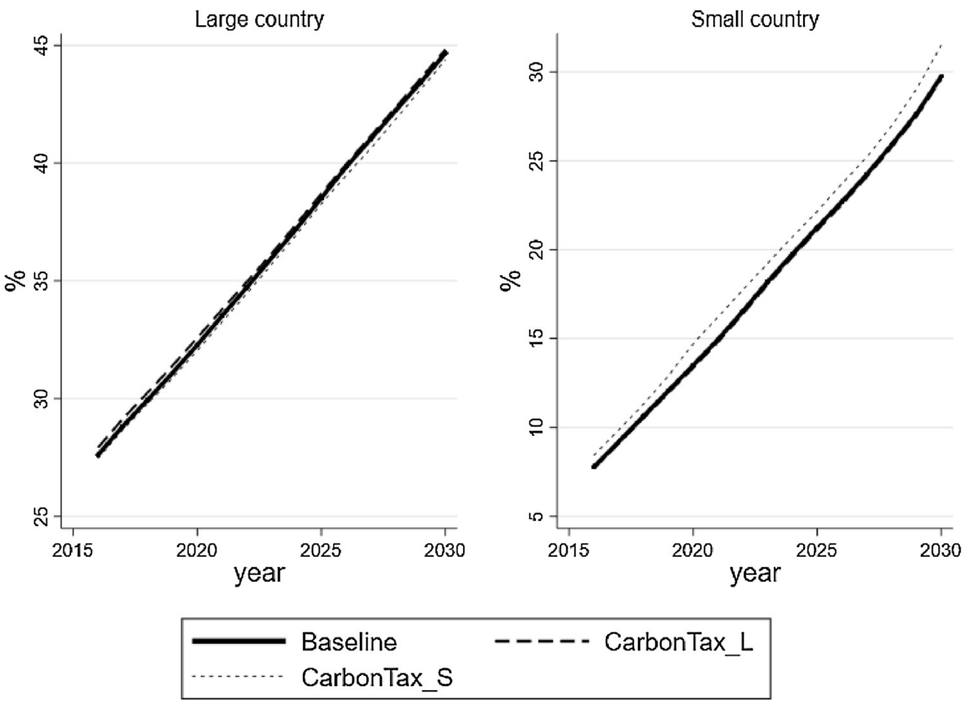

Fig. 12. Share of RES in domestic generation, large and small country, per variant, 2016–2030.

effect does not fully neutralize the effect of the carbon tax. This result is related to the fact that the price of CO_2 may be zero from time to time (Fig. 6). If the price of CO_2 is zero any other reduction in the demand for carbon permits cannot have any effect on the price anymore. Hence, we find that the combination of different policy measures to reduce carbon emissions may still be effective despite the interaction effects.

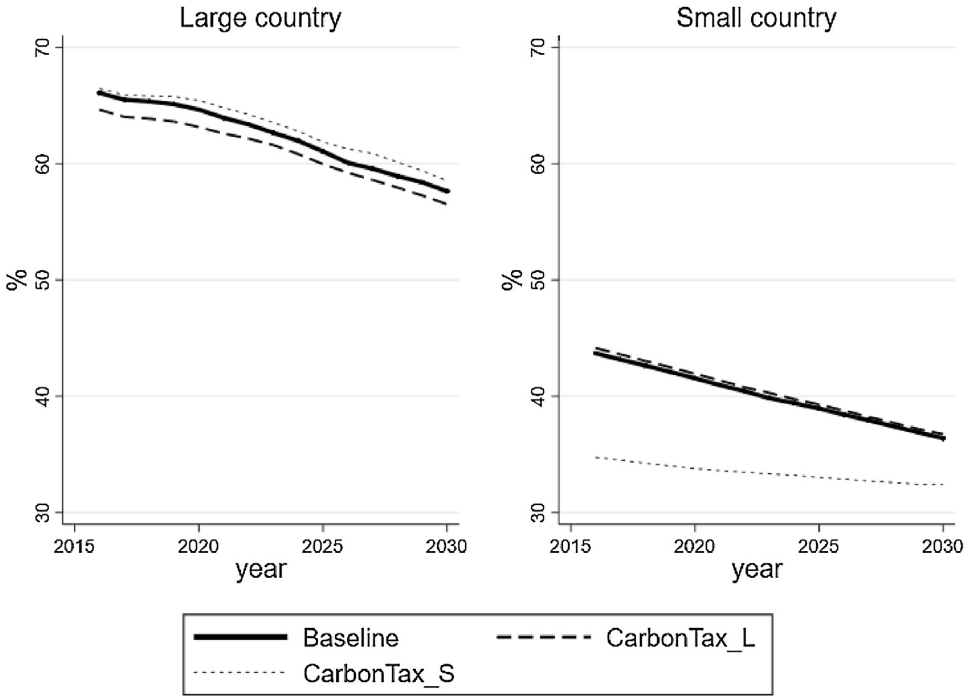

Fig. 13. Utilisation of fossil-fuel capacity, Baseline and variant with carbon tax in large country, large and small country, 2016–2030.

4.2.4. *Welfare effects of carbon tax*

Imposing a carbon tax raises the marginal costs of electricity production which increases the electricity price. As a result consumers have to pay more, which reduces their consumer surplus. As the impact of the carbon tax on electricity prices is the biggest in the domestic market, because of cross-border capacity constraints, the consumer welfare is most strongly affected by the domestic carbon tax (Fig. 14).

Remarkably the producer surplus increases as a result of the carbon tax. Although the carbon tax raises the costs of the conventional producers, the producers of RES do not have to pay this tax, but they do benefit from the resulting electricity prices. Hence, both consumers and RES producers benefit from the introduction of a carbon tax, while the producers of conventional power faces a loss in terms of lower production levels and lower profits per unit.

4.2.5. *Sensitivity analysis*

When we lower the emission cap, subsequently we observe a lower carbon emission level and a higher carbon price (Fig. 4). Because of the higher carbon price, we find higher electricity wholesale prices in the small country: the price-reducing effect of the increase in RES capacity is completely neutralized by the price-increasing effect of the tighter carbon market (see Fig. 3). We also observe a stronger spillover effect of a carbon tax on fossil-fuel production: the utilisation of the

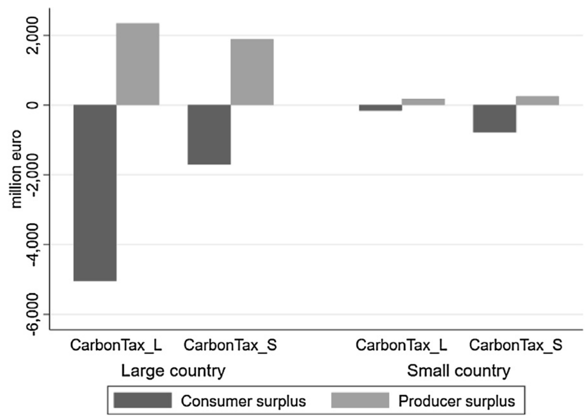

Fig. 14. Change in consumer and producer surplus in two variants compared to the Baseline, in both countries in 2030.

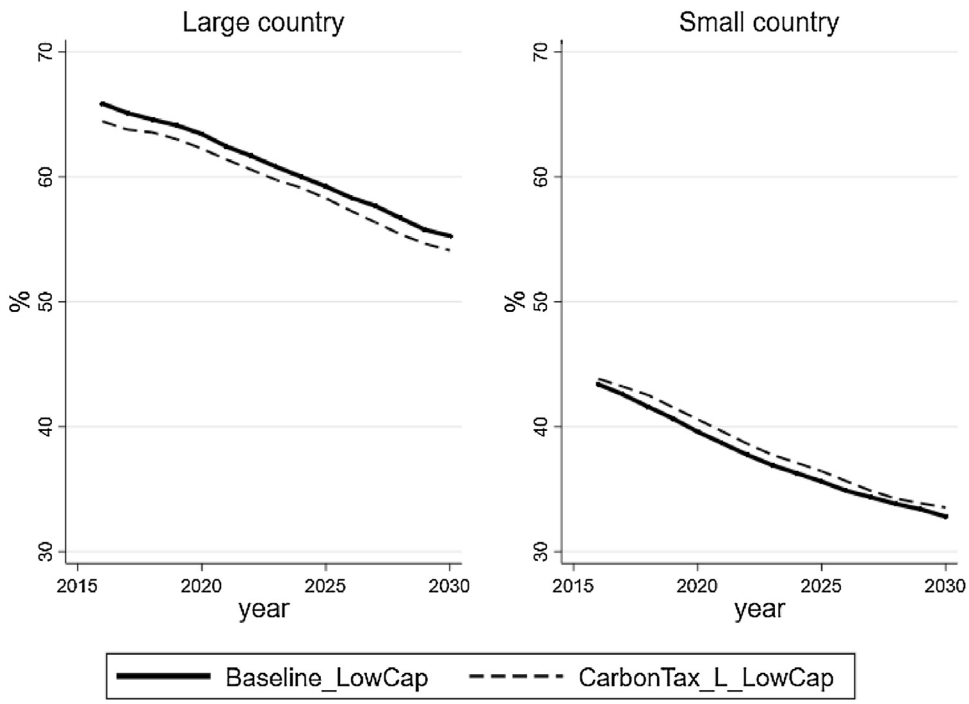

Fig. 15. Utilisation of fossil-fuel capacity in the Baseline_LowCap and CarbonTax_LowCap, 2016–2030.

fossil-fuel plants increases more strongly due to the introduction of the carbon tax in one country (see Fig. 15). This implies that in case of tighter emissions-trading system, the international spillover effect of national policies, like a carbon tax, are larger. More importantly, because of the stronger effect on the CO_2 prices, there is less effect on CO_2 emissions (see Fig. 5). This is related to the fact that in case of a lower cap the carbon prices are less often zero which makes it possible to stronger obtain the waterbed effect which neutralizes emission reductions resulting from the carbon tax.

When we add the possibility of banking permits and using them in the next period, the results remain basically the same (Fig. 16). In case of banking, the CO_2 price appears to be zero in both the Baseline and the policy variant with a carbon tax. This result follows from the fact that banking can result in a higher supply in the next period when there is an oversupply in the previous one. Hence, banking can make the redundancy of the emission trading scheme even stronger. As a consequence, introducing a carbon tax when the emissions trading market is loose, for instance because of the possibility of banking, this combination of climate-policy measures may result in a reduction of carbon emissions. The general lesson here is that regulatory measures which make the cap in the emissions trading scheme less binding, may reduce the waterbed effect.

5. Concluding remarks

In this paper we have explored the conditions under which interaction effects occur between different types of climate-policy measures. Governments are combining different types of policy measures in order to realise their ambitious objectives regarding the reduction of carbon emissions. It is well established in the literature that the combined effect may be lower than the sum of the individual effects. Combining subsidies for renewable energy or taxes on fossil fuels together with a cap-and-trade system suffers from the waterbed effect. Moreover, national policies to reduce domestic emissions may be offset by international spillover effects. The question we have explored is whether this offsetting effect always occurs or whether it may be subject to specific conditions. This topic is relevant because in the EU, each country has the freedom to choose its own national energy policy despite of European climate-policy objectives. European countries apply a mixture of different types of policy measures which make it highly relevant to analyze the nature of and the conditions for the interaction effects.

Using a numerical partial two-country equilibrium model of the power market which also includes a cap-and-trade carbon system, we find spillover effects due to the integration of the two markets. Imposing a fossil-fuel tax in one country leads to a higher cost for fossil-fuel producers. Hence, this country imports more from the neighboring country. As a result of this, we observe a higher utilization of fossil-fuel capacity in the neighboring country. The spillover effects are smaller when the carbon tax is introduced in the small country instead of in the large country. Both the CO_2 price and the overall CO_2 emissions in the region are less affected then when the large country implements a carbon tax. The lower the cap in the emissions-trading system, the stronger this effect appears to be. This result indeed shows that national policies to

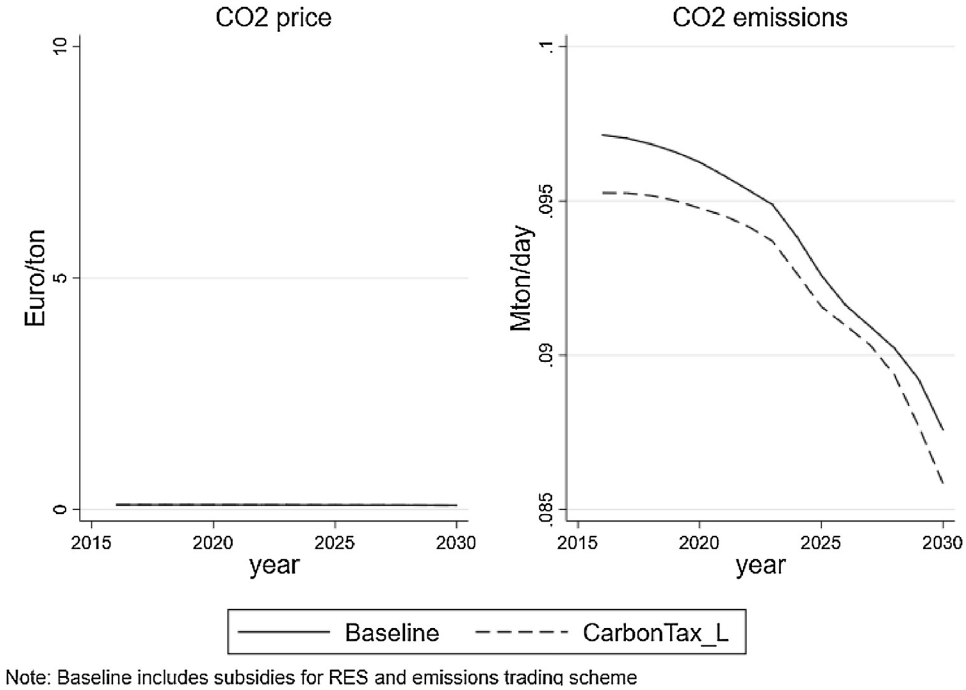

Fig. 16. CO_2 price and emissions with the option of banking permits, Baseline and CarbonTax_L, 2016–2030.

reduce carbon emissions may be offset by international spillover effects. Coordination of such policies may improve the effectiveness of such policies.

However, we find that the waterbed effect does not always hold. It appears that adding other climate-policy measures to an emissions-trading system may have a net effect on the level of carbon emissions. This result comes from the fact that the carbon price in the trading scheme has a floor, i.e. it can never be lower than zero. If subsidies for renewable energy result in a large amount of renewable-energy capacity this may in some periods result in an overall demand for carbon permits being below the supply of permits which brings the carbon price to zero. In such circumstances, giving more subsidies for renewables or imposing a tax of fossil fuel reduce the emissions by fossil-fuel plants without being neutralized by a waterbed effect. Hence, we find that the waterbed effect only holds if the cap-and-trade system is constantly binding, which means that there is always a positive price for the carbon permits. The probability of always binding emissions-trading system, however, reduces if countries keep increasing the size of installed RES capacity as is currently the case in many European countries. Moreover, a similar effect may occur if regulatory measures are taken which make the emissions-trading scheme less tight, such as banking which increases the time flexibility of participants within the scheme. The policy consequence of this finding is that national climate policies such as subsidy schemes for renewables may have a positive effect on reduction of carbon emissions, although the general literature says that such cannot be the case when an emissions-trading scheme exists.

These findings are based on a numerical analysis of a concise model of the electricity market. The numerical simulations do not enable us to draw general conclusions, as the findings may be sensitive to the chosen parameter values. Nevertheless, a numerical application of a model does give insights in the interrelationships of a number of factors affecting the market. Because of its theoretical and stylized nature, this model analysis does not give precise estimates of the size of the relationships and the probability of the situations in which the interaction effect do not occur. Although the model has a rather detailed representation of the electricity sector, it largely ignores the sector's interactions with the rest of the economy, such as fossil fuel production, aggregate investment and employment. Such interactions are also important for evaluating the effectiveness of climate policies. Empirical research is needed to obtain precise estimates for the magnitude of actual interaction effects between current climate-change policies.

As we only focused on the occurrence and absence of interaction effects of different type of climate policies, we did not discuss the efficiency of these interaction effects. Although adding a carbon tax on top of an emissions trading scheme may result in more emissions reductions as the waterbed effect does not always work, this does not mean that such a policy is efficient. In order to analyse the efficiency effects of climate policies, a more general equilibrium approach is needed taking into account more kinds of interactions within the economy.

Appendix A. Fossil fuel plants investment

When the expected production by Renewable Energy Supply (RES) is low or zero, the need for fossil fuel production might exceed the current generation capacity. As a result of this, electricity scarcity prices occur, see also ten Cate and Lijesen (2004). In the fossil-fuel investment decisions, we also take import and export into account. Electricity importing companies are modelled as price-takers. Let q^I_{yh} be the total electricity import. Following Mulder et al. (2015), the supply of the importers is approximated by a linear supply function,

$$q^I_{cyh} = \delta p_{cyh}, \tag{15}$$

and the export amount by firm i is q^{iE}_{cyh}. We have the following equation for scarcity prices,

$$Q^F_{cy} + \delta p_{cyh} + \left(\alpha_{cyh} + \beta p_{cyh}\right) - \sum_i q^{iE}_{cyh} = a_h - b_h p_{cyh}. \tag{16}$$

Note that the first term Q^F_{cy} denotes the fossil-fuel generation capacity, the second term $\left(\delta p_{cyh}\right)$ on the left-hand side of Eq. (16) denotes the import amount,[12] the third term $\left(\alpha_{cyh} + \beta p_{cyh}\right)$ denotes the production amount by fringe suppliers and the fourth term $\left(\sum_i q^{iE}_{cyh}\right)$ denotes the electricity export amount which is modelled exogenously. The right-hand side of Eq. (16) denotes the aggregate demand at a certain electricity price level.

The fossil-fuel plants investments ΔQ^F_{cy} are considered in a competitive setting in which firms cannot behave strategically and exercise market power. Assuming perfect foresight, expected long-run marginal revenues should be equal to long-run marginal costs. Following ten Cate and Lijesen (2004), we have the following: the price per MWh which is required to keep demand down to capacity (Eq. (16)), minus marginal running costs per MWh, accumulated over the hours during which capacity is a binding constraint, equals the incremental annualized cost of building an extra MW. Suppose the annualized fossil fuel investment costs are c_F and a linear functional form of investment costs,

$$E\left[\left(\sum_{h \in \{q^F_{cyh} = Q^F_{cy} + \Delta Q^F_{cy}\}} \left(p_{cyh} - m_c\right)\right) | w_h\right] = c_F, \tag{17}$$

where m_c denotes the constant fossil fuel production costs. The expression $\{q^F_{cyh} = Q^F_{cy} + \Delta Q^F_{cy}\}$ denotes the set of hours when the capacity constraint is binding. Hence, the investment in fossil-fuel plants ΔQ^F_{cy} should be set at a level that equalizes expected marginal benefits (LHS of Eq. (17)) and marginal costs (RHS of Eq. (17)).

Appendix B. RES investment

We assume that the investments in RES depend on government subsidies. Suppose the RES subsidy budget for wind parks is B^W_{cy} and the budget for solar cells is B^S_{cy}. Moreover, we assume that the budget is financed by a tax on electricity consumption. The investment costs for wind parks and solar cells are denoted by c^W_y and c^S_y, respectively. The newly installed capacities for centralized power producers (ΔQ^W_{cy}) are calculated as follows:

$$\Delta Q^W_{cy} = \frac{B^W_{cy}}{c^W_y}.$$

Similarly, the newly installed capacities for decentralized power producers (ΔQ^S_{cy}) are calculated as follows:

$$\Delta Q^S_{cy} = \frac{B^S_{cy}}{c^S_y}.$$

Appendix C. Optimal production amount by centralized power producers

The electricity market is modelled as a market with imperfect competition where the supply is determined by a limited number of strategic suppliers and a fringe supply consisting of weather dependent wind and solar production as well as CHP production which acts as a price taker. The strategic suppliers, which are supposed to have both fossil-fuel plants and wind turbines, compete in quantities (Cournot competition). The suppliers sell their production in both forward and spot markets. Each firm has an incentive to maximize revenues in forward markets as this reduces the market power of other firms in the

[12] We could also incorporate the import constraint in the equation.

spot market (Allaz and Vila, 1993). In order to determine the optimal production quantity by the strategic players using their fossil-fuel plants, we need to estimate the amount sold in the forward markets. First we determine the optimal production given the strategic game in the spot market and then determine how this depends on the forward sales. After determining the marginal impact of forward sales on the optimum production amount, we are able to determine the optimal production level.

The production game for firm $i \in N_c$ in the spot market is given by,[13]

$$\max_{q^{iF}_{cyh}} \quad p_{cyh}(q^i_{cyh} - q^{if}_{cyh}) - m_c q^{iF}_{cyh},$$
$$\text{s.t.} \quad q^i_{cyh} = q^{iF}_{cyh} + q^{iW}_{cyh}.$$

where m_c is the constant variable costs for firm i in country c to use the conventional resources to generate electricity and $p_{cyh} = \frac{a_h - \alpha_{cyh} - q^i_{cyh} - q^{-i}_{cyh}}{b_h + \beta}$. The first order conditions for firm i read,

$$\frac{a_h - \alpha_{cyh} - \left(q^{-iF}_{cyh} + q^{-iW}_{cyh}\right) - 2\left(q^{iF}_{cyh} + q^{iW}_{cyh}\right)}{b_h + \beta} + \frac{q^{if}_{cyh}}{b_h + \beta} - m_c = 0, \tag{18}$$

Eq. (18) holds for every firm i and we can write the system of equations for the first order conditions of each producer into matrix form as follows:

$$\begin{bmatrix} 2 & 1 & \cdots & 1 \\ 1 & 2 & \cdots & 1 \\ 1 & 1 & \cdots & 1 \\ \cdots & \cdots & \cdots & \cdots \\ 1 & 1 & \cdots & 2 \end{bmatrix} \begin{bmatrix} q^{1F}_{cyh} \\ q^{2F}_{cyh} \\ \cdots \\ \cdots \\ q^{n_cF}_{cyh} \end{bmatrix} = \begin{bmatrix} a_h - \alpha_{cyh} + q^{1f}_{cyh} - q^{-1W}_{cyh} - 2q^{1W}_{cyh} + m_c(b_h + \beta) \\ a_h - \alpha_{cyh} + q^{2f}_{cyh} - q^{-2W}_{cyh} - 2q^{2W}_{cyh} - m_c(b_h + \beta) \\ \cdots \\ \cdots \\ a_h - \alpha_{cyh} + q^{n_cf}_{cyh} - q^{-n_cW}_{cyh} - 2q^{n_cW}_{cyh} - m_c(b_h + \beta) \end{bmatrix}.$$

The above matrix solve $q^{iF}_{cyh}, i \in N_c$ as a function of $q^{1f}_{cyh}, q^{2f}_{cyh}, \ldots, q^{n_cf}_{cyh}$. Note that we also have $q^{iW}_{cyh} = q^{jW}_{cyh}$, $i, j \in N_c$, i.e., the wind power generation is also symmetric among all producers. We solve the above matrix and obtain the following solution for the optimal generation by fossil-fuel plants of i, $i \in N_c$,

$$q^{iF}_{cyh} = \frac{a_h - \alpha_{cyh} + q^{if}_{cyh} - q^{-iW}_{cyh} - 2q^{iW}_{cyh} - \sum_{j \in N_c, j \neq i}\left(q^{jf}_{cyh} - q^{if}_{cyh}\right) - m_c(b_h + \beta)}{n+1}, \quad i, j \in N_c. \tag{19}$$

Hence, the marginal impact of forward sales on the production quantity is determined by:

$$\frac{\partial q^{iF}_{cyh}}{\partial q^{if}_{cyh}} = \frac{n}{n+1}, \tag{20}$$

$$\frac{\partial q^{jF}_{cyh}}{\partial q^{if}_{cyh}} = -\frac{1}{n+1}, \tag{21}$$

where $i, j \in N_c$ and $j \neq i$.

Now we move to the stage of firms choosing the optimal forward positions. According to Allaz and Vila (1993), we have the following maximization problem,

$$\max_{q^{if}_{cyh}} \quad p^f_{cyh} q^{if}_{cyh} + p_{cyh}(q^i_{cyh} - q^{if}_{cyh}) - m_c q^{iF}_{cyh},$$
$$\text{s.t.} \quad q^i_{cyh} = q^{iF}_{cyh} + q^{iW}_{cyh}.$$

According to the arbitrage condition, it should hold that $p^f_{cyh} = p_{cyh}$. Hence, the above maximization problem can be simplified as,

$$\max_{q^{if}_{cyh}} \quad p_{cyh} q^i_{cyh} - m_c q^{iF}_{cyh},$$
$$\text{s.t.} \quad q^i_{cyh} = q^{iF}_{cyh} + q^{iW}_{cyh}.$$

[13] For notational convenience, we suppress the expectation sign for q^{iW}_{cyh} from now on.

where $p_{cyh} = \frac{a_h - q^{-i}_{cyh} - q^{i}_{cyh} - \alpha_{cyh}}{b_h + \beta}$. Taking first order conditions with respect to q^{if}_{cyh}, we obtain the following equation for firm i,

$$\left(a_h - \alpha_{cyh} - m_c\left(b_h + \beta\right) - q^{iF}_{cyh} - q^{-iF}_{cyh} - q^{iW}_{cyh} - q^{-iW}_{cyh}\right)\frac{\partial q^{iF}_{cyh}}{\partial q^{if}_{cyh}} - \left(q^{iF}_{cyh} + q^{iW}_{cyh}\right)\left(\frac{q^{iF}_{cyh}}{q^{if}_{cyh}} + \sum_{j \in N_c, j \neq i}\frac{\partial q^{jF}_{cyh}}{\partial q^{if}_{cyh}}\right) = 0, \tag{22}$$

where $\frac{\partial q^{iF}_{cyh}}{\partial q^{if}_{cyh}}$ and $\frac{\partial q^{jF}_{cyh}}{\partial q^{if}_{cyh}}$ are given by (20) and (21), respectively. Due to the fact that firms are symmetric in terms of their constant variable costs, their final production amounts in the equilibrium should be the same as well. Plugging Eqs. (19)–(21) into (22), we obtain the following result for the optimum production level per firm,

$$q^{iF}_{cyh} = \frac{n_c\left(a_h - \alpha_{yh} - m_c(b_h + \beta)\right) - q^{iW}_{cyh} - n_c(q^{iW}_{cyh} + q^{-iW}_{cyh})}{n_c^2 + 1}, \tag{23}$$

Appendix D. Calculation of the aggregate demand function

Suppose we want to calculate the aggregate hourly dependent demand function,

$$q_{cyh} = a_h - b_h p_{cyh},$$

and the objective is to calculate parameters a_h and b_h. Given the price elasticities ε_h in the literature and observed quantity $\tilde{p}_{cyh}$ and output $\tilde{Q}_{cyh}$ in a load profile, we use the following formula to calculate a_h and b_h,

$$\varepsilon_h = -\frac{dQ/Q}{dP/P} = -\frac{dQ}{dP} \times \frac{P}{Q} \Rightarrow b_h = \varepsilon_h \frac{\tilde{Q}_{cyh}}{\tilde{p}_{cyh}}, \quad a_h = \tilde{Q}_{cyh} + b_h \tilde{p}_{cyh}.$$

Note that the above formula is implemented to calculate the aggregate demand function in the small country and the aggregate demand function for the large country is obtained by scaling up the demand function of the small country.

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